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ON THE NATURE OF THE PLANETARY COMPANIONS OF STARS

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ON THE NATURE OF THE PLANETARY COMPANIONS OF STARS

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Introduction

The author (Kumar 1963a; this will be referred to as paper I) has recently studied the properties of contracting stars of mass between 0.09 $M_\odot$ and 0.04 $M_\odot$. Here we shall study the same problem for a star of mass 0.01 $M_\odot$. We want to study this problem to find out what happens to a star of mass around 0.01 $M_\odot$ when it is formed out of a gaseous medium. In particular, we are interested in explaining the nature of unseen planetary companions of stars. The unseen companions generally have masses in the range 0.0015 to 0.02 (solar units). As a typical object in this range, we study here the properties of a contracting star of mass 0.01. We have listed the known unseen companions in Table 1.

Properties of a Contracting Star of Mass 0.01 $M_\odot$

When an object of mass 0.01 is formed out of a gaseous medium, it begins to contract under its own gravitation. We shall assume here that the star can be represented by a sphere of polytropic index 1.5. This assumption seems to be justified in the light of Hayashi's work (1962). Hayashi has shown that the contracting stars of low mass are in convective equilibrium. We choose the following chemical composition for our star: $X = 0.62$, $Y = 0.35$, $Z = 0.03$.

To compute the temperature, density and pressure at the center of the contracting star, we use here the procedure given in paper I. However, the assumption of complete ionization of the stellar material is no longer valid, for we do not expect temperatures and densities sufficiently high for this purpose. At the temperatures inside a contracting object of mass 0.01, hydrogen will be completely ionized. As far as the heavier elements are concerned they will be in various stages of ionization. Since we are interested in obtaining approximate results, we will compute models for two extreme cases for the state of ionization. First, we compute models for the case when all the elements are completely ionized. Second, we assume that hydrogen is completely ionized, helium is singly ionized and heavier elements are ionized in such a way that each atom has lost Z/2 electrons, where Z is the atomic number. For the second case, the molecular weight is given by

$$\frac{1}{\mu} = 2X + \frac{Y}{2} + \frac{Z}{4} \tag{1}$$

The actual state of ionization should be somewhere in between these two extreme cases. The difference in the physical structure caused by changing the ionization from one extreme to another is not large and therefore we are presenting here the results for an "average" ionization. The average state of ionization is approximately in the middle of two extremes. The variation of the temperature T_c and the temperature ρ_c with radius R is shown in Figure 1. In this figure we have given three curves showing the variation of T_c with R; the two broken curves correspond to the two extreme ionization states, whereas the solid curve corresponds to the mean ionization. The solid vertical line gives the limiting radius for a star of mass = 0.01 corresponding to the mean ionization. These results show clearly that the object under study becomes a completely degenerate object or a black dwarf as a result of gravitational contraction. Since the maximum central temperature during the contraction is only 2.4×10^5 degrees, no hydrogen burning will take place in the star. Also, it is highly unlikely that the nuclear reactions involving the destruction of Deuterium or Lithium will take place.

Figure 2 shows the temperature - density diagram for the models corresponding to the mean ionization. As the star contracts, it becomes more and more degenerate and ultimately it reaches the stage of complete degeneracy. It is proposed here that the unseen companions of very low mass are probably the degenerate objects formed by the above-mentioned process.

Computation of the Time-scale

It is of great interest to compute the time scale up to the stage of maximum central temperature. Kumar (1963b) has given the following simple expression for the time scale $t_{H.K}$ for a contracting object:

$$t_{H.K} = 4.98 \times 10^9 \frac{M^2}{T_3{}^4 R^3} \text{ years} \qquad (2)$$

where M and R the mass and radius in solar units and T_3 is the constant temperature in thousands of degrees. This expression was derived assuming that the contracting stars of low mass evolve vertically downwards in the H-R diagram. Hayashi (1962) and Kumar and Upton (1963) have shown that this assumption is correct and, therefore, equation (2) gives the time scale accurately. In order to compute $t_{H\cdot K}$ we must know T_3 and R. The stage of maximum central temperature is reached at $R \simeq .20$. For the effective temperature during vertical evolution we take a value of 2000°K as a reasonable value. The actual temperature cannot be appreciably different from this value for the following reasons. The temperatures for two stars of very low mass are given below:

L726-8 A (0.044)	2750°K	(dM6)
L726-8 B (0.035)	2750°K	(dM6)

Also, the temperature for van Biesbroeck's star +4°4048B which probably has a mass less than 0.07 (Kumar 1963c) is about 2000°K. Secondly, it is clear from theoretical work of Kumar and Upton (1963) that the effective temperature of contracting stars in their vertical evolution decreases <u>very</u> slowly as the mass is decreased. Thus the temperature of a star of mass 0.01 should be quite close to the temperature of L726-8B (0.035). Therefore, our time scale for a star of mass 0.01 will not be in great error if we assume a value of 2.0 for T_3. From equation (2) we have

$$t_{H\cdot K} \simeq 4 \times 10^6 \text{ years}$$

This is an exceedingly short time scale and we may say that there exist many stars of mass around 0.01 which have evolved beyond the stage of maximum central temperature. After this stage, these stars gradually cool towards the stage of complete degeneracy and they eventually become invisible black dwarfs. In all likelihood, the unseen planetary companions of some stars are such objects.

The Distinction Between a Planet and a Star

In astronomical literature (Russell 1943), it is often stated that at a certain mass there exists a dividing line between planets and stars. The mass of Jupiter, which is the most massive planet in the solar system, is 0.001. Unseen companions of stars have masses in the range 0.0015 to 0.02. As has already been pointed out in paper I, all population I stars having mass below 0.07 become completely degenerate objects or black dwarfs as a result of gravitational contraction. In view of this conclusion, the distinction between a star and a planet is not clear because a planet can be approximately represented by a black dwarf. But at the same time we do not know whether the planets (specially the terrestrial planets) in our solar system were formed by the contraction of gaseous objects. Therefore, it seems appropriate to give the name "planetary object" to all those objects which become black dwarfs as a result of gravitational contraction. At the present time, we do not know whether the planets in the solar system have been formed according to this definition, but a planetary object can have any mass below 0.07. Thus we have two groups of objects: the first group consists of stars that go through the main sequence stage and the second group of objects which do not go through this stage. Under the second group we can include stars such as L726-8 and planetary objects such as the unseen companions of very low mass.

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TABLE 1

LIST OF THE PLANETARY COMPANIONS

STAR	MASS OF THE PLANETARY COMPANION	
BD + 20° 2465	≥ 0.02	(van de Kamp 1958)
Ci 2354	≥ 0.02	(van de Kamp 1958)
η Cas*	$\simeq 0.01$	(van de Kamp 1956)
Lalande 21185	$\simeq 0.01$	(Lippincott 1963)
Krueger 60A†	≥ 0.009	(van de Kamp 1956)
61 Cygni	≥ 0.008	(van de Kamp 1958)
Barnard's Star	$\simeq 0.0015$	(van de Kamp 1963)

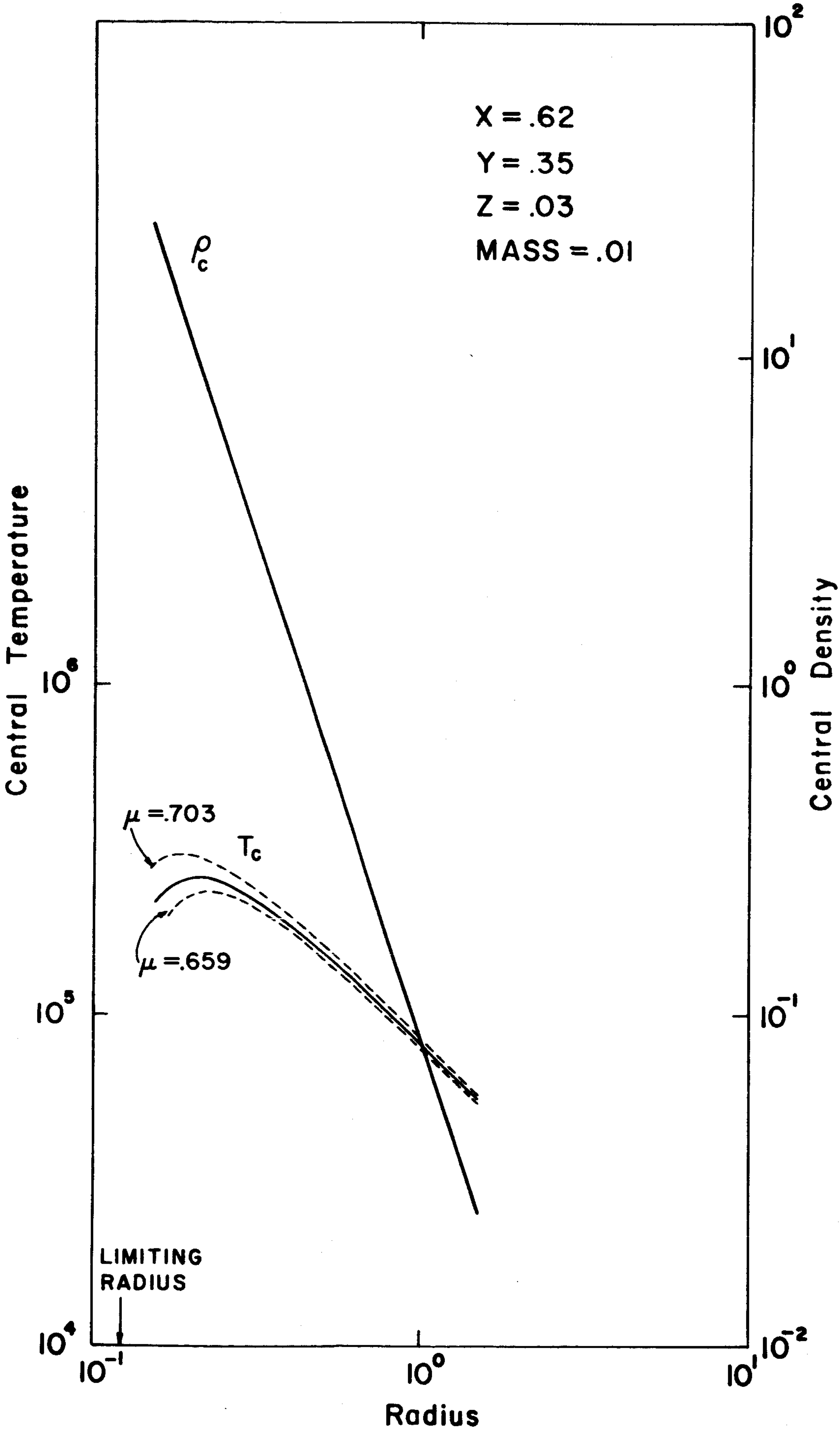
* The existence of the planetary companion has not been completely established (A.J., 60, 452, 1955.)

† If a companion exists, its mass lies between 0.009 and 0.025 (A.J., 58, 140, 1953.)

CAPTIONS FOR FIGURES

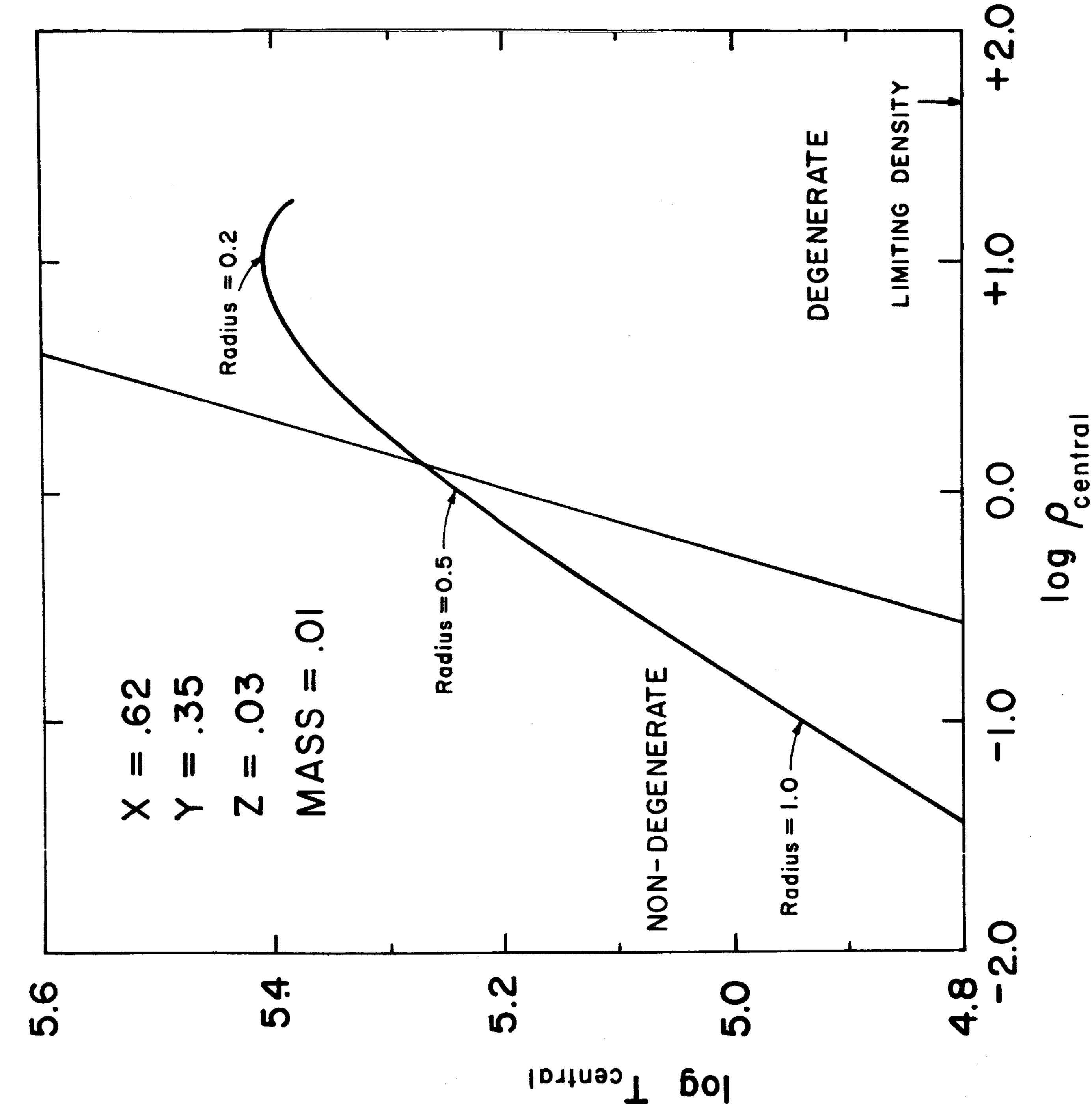
Figure 1 - The variation of the temperature T_c and density ρ_c with radius R.

Figure 2 - The temperature density diagram. The straight line divides the diagram into degenerate and non-degenerate regions.



X = .62
Y = .35
Z = .03
MASS = .01
ρ_c
T_c
μ =.703
μ =.659
Central Temperature
Central Density
LIMITING RADIUS
Radius
10^{-1}
10^0
10^1
10^4
10^5
10^6
10^{-2}
10^{-1}
10^0
10^1
10^2

Figure 1



X = .62
Y = .35
Z = .03
MASS = .01
DEGENERATE
NON-DEGENERATE
LIMITING DENSITY
Radius = 0.2
Radius = 0.5
Radius = 1.0
log $\rho_{central}$
log $T_{central}$
-2.0
-1.0
0.0
+1.0
+2.0
4.8
5.0
5.2
5.4
5.6

Figure 2